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Study of LARP IR Quadrupoles Based on Racetrack Coils

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Introduction

After the Large Hadron Collider (LHC), being constructed at CERN, operates for several years at nominal parameters, it will be necessary to upgrade it for higher luminosity [1, 2]. Replacing the present 70-mm NbTi low-beta quadrupoles in the inner triplets with higher performance magnets based on advanced superconducting materials and magnet technologies is one of the most straightforward ways in this direction [3].

Conceptual design studies performed in the framework of US LHC Accelerator Research Program (LARP) show that high-performance Nb_3Sn strands to be available within the next few years allow expanding the quadrupole aperture up to 110 mm using a 4-layer shell-type coil and providing the same 200 T/m field gradient with 20% margin as the present 70-mm magnets [4]. An alternative approach to the quadrupole design is based on a simple flat racetrack coil. This approach deserves attention since it is seen at present time as more simple design and technological approach to the high field accelerator magnets based on brittle Nb3Sn superconductor.

This note discusses the possibilities and limitations of large-aperture racetrack quadrupole designs for the LHC luminosity upgrade and compares them to the equivalent shell-type quadrupole magnets.

Aperture issues

Since racetrack quadrupoles have square apertures, they cannot be directly compared to shell-type magnets with round apertures. In order to make a fair comparison, one should compare magnets with equivalent physical apertures e.g. apertures which can accommodate two beams of given sizes and provide similar beam position with respect to magnet axis.

According to the estimations presented in [3], the maximum possible beam size in the LHC single-aperture inner triplet with 110 mm quadrupoles and β_{max}=15 km is 23.5 mm, which includes $9\sigma_{max}$ beam size, 20% β-beating and 8.6 mm as the sum of alignment and orbit errors. In 110 mm shell-type quadrupole with round aperture two such beams can be accommodated with the distance of each beam from the magnet axis of 24 mm. The result includes the 3 mm thick beam pipe and the 4.5 mm annular channel for liquid He. The same two beams can be accommodated on the same distance from the quadrupole axis in the racetrack quadrupole with squire aperture. Figure 1 shows the sizes and positions of two beams, the beam pipe cross-section and major dimensions for both cases. Beam tube thickness and area of the cooling channel between coil and beam tube in the racetrack magnet are the same as in the shell type quadrupole.

Thus, according to the picture, racetrack quadrupole with 92 mm aperture in the pole plane and 130 mm in the midplane has the same physical aperture as 110 mm shell type magnet with round aperture. For the sake of consistency, the coil apertures of the racetrack quadrupole magnets presented in this note is always counted in the pole plane.

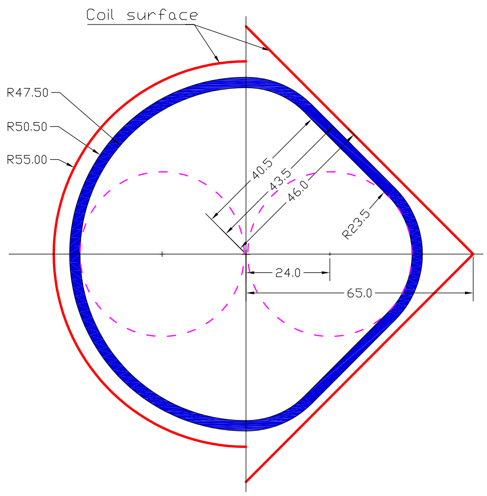

Figure 1. Equivalent shell-type (left) and racetrack (right) coil apertures.

Racetrack coil designs

Racetrack quadrupoles with 90-100 mm apertures were studied. For correct comparison they were optimized with the same basic parameters and boundary conditions as the shell type quadrupoles [4]:

- $J_{non\text{-}Cu}(12T,4.2K) = 3000\ A/mm^2$;
- Round iron yoke, $\mu = 1000$;
- Coil-yoke space in the midplane = 15 mm.

Cables in both racetrack magnets have the same 0.8-mm Nb_3Sn strand with Cu:nonCu ratio of 1.2 and cable packing factor of 0.89. The cable width and number of strands for 90-92 mm quadrupoles were determined by the target quench gradient of 240 T/m. The cable parameters for 100 mm quadrupole were chosen based on the cable mechanical stability considerations. It resulted in slightly lower quench gradient of this magnet. Table 1 summarizes the cable parameters in 90-100 mm designs. The cable insulation thickness was 0.2 mm in all designs.

Table 1: Cable parameters.

Coil aperture	90 mm	92 mm	100 mm
Number of strands	28	36	42
Cable width, mm	11.343	14.599	17.041
Cable thickness, mm	1.433	1.433	1.433

Figures 2 show 90-100 mm optimized coil cross-sections with the field quality diagrams and field distribution in the coils. In order to maximize the use of the midplane space and minimize conductor volume the coils have interleaving design, which requires four different double-pancake coils.

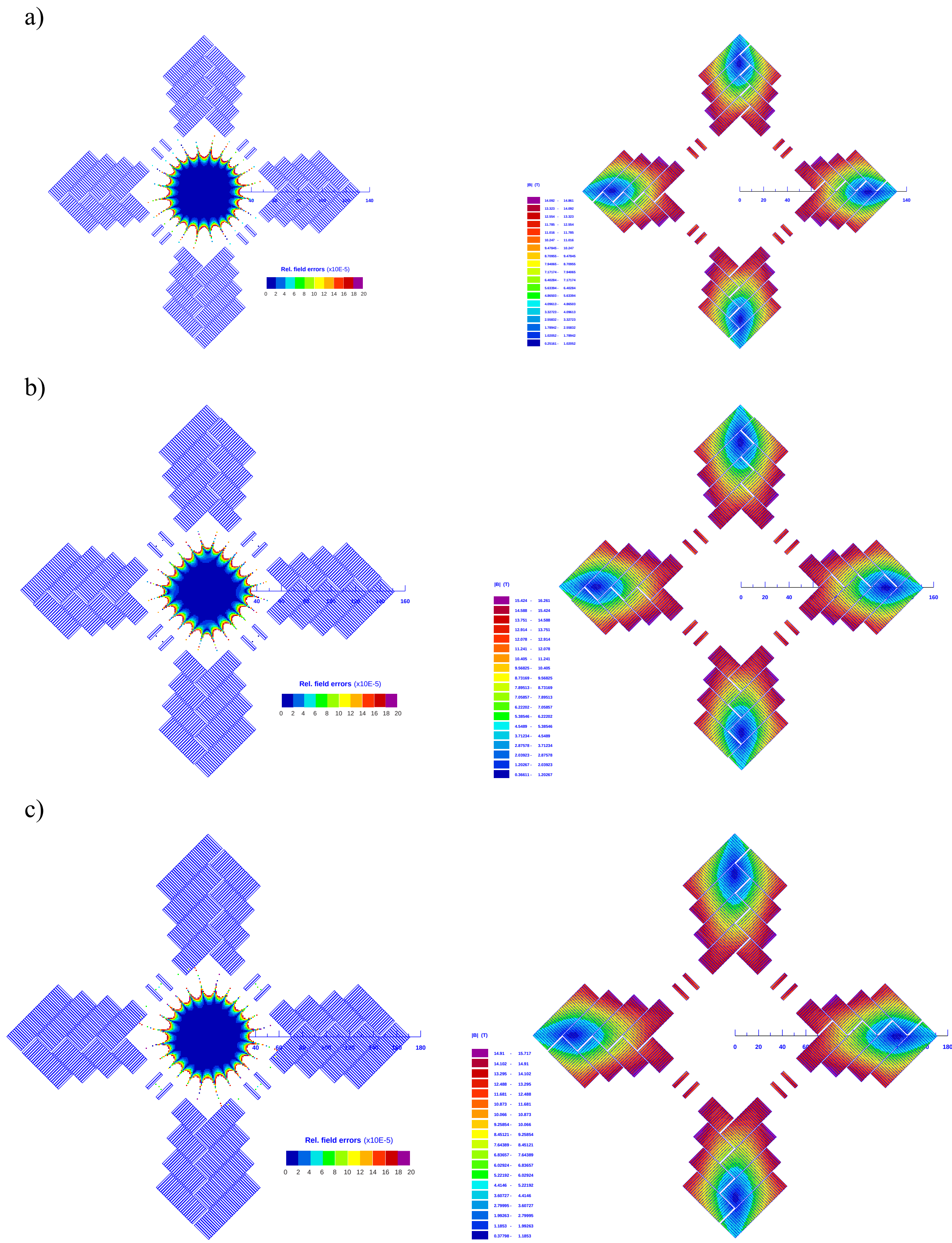

Figure 2. Racetrack quadrupole coil cross-sections with apertures in the pole plane: a) – 90 mm, b) – 92 mm, c) – 100 mm.

The coil cross-sections were optimized for the best field quality in the aperture for the given set of parameters. In 92 mm design the small b_{10} component of opposite to b_{14} sign was artificially introduced to gauge a possibility of increasing the good field region in the midplane of the racetrack quadrupoles. It provided rather square than round shape of the good field region with some gain of field quality in the horizontal and vertical planes.

Racetrack and shell-type quadrupole Parameters

Table 2 summarizes the main design parameters of the racetrack and shell-type quadrupoles with different apertures. It allows comparison of relevant parameters of two quadrupole designs with the same round aperture (100 mm racetrack and 100 mm shell-type quad) or the same equivalent apertures as it was defined above (92 mm racetrack and 110 mm shell-type quad).

Table 2. Parameters of the racetrack and shell type quadrupole magnets.

Parameter		Unit	Racetrack			Shell		
			90mm	**92mm**	100mm	90mm	100mm	**110mm**
N of layers			4	**4**	4	2	4	**4**
N of turns			332	**368**	388	144	228	**248**
Coil area (Cu + nonCu)		cm^2	96.53	**133.08**	169.22	48.09	59.31	**84.88**
NonCu Jc at 12 T, 4.5 K		A/mm^2	3000	**3000**	3000	3000	3000	**3000**
Quench gradient		T/m	240.8	**240.4**	226.4	260.6	258.2	**248.9**
Quench current		kA	11.87	**13.70**	14.52	17.64	12.31	**14.13**
Peak field in the coil		T	14.9	**15.3**	15.7	13.5	14.5	**15.3**
Inductance		mH/m	30.86	**33.44**	39.94	4.86	14.71	**17.46**
Stored energy @ 205 T/m		kJ/m	1575.6	**2282.0**	3452.0	468.2	702.9	**1181.4**
Forces/octant at 205 T/m	Fx	MN/m	3.67	**4.42**	6.10	1.50	2.38	**3.44**
	Fy	MN/m	-3.78	**-4.83**	-3.18	-1.92	-2.39	**-3.42**

As it can be seen from Table 2, the large-aperture racetrack quadrupoles are less efficient than the shell-type quadrupoles. They provide smaller quench gradient at larger coil volume, stored energy and Lorentz forces in the coil. Even the racetrack quadrupole with 92 mm aperture is less efficient than the equivalent 110 mm shell-type magnet by all major parameters. The coil area is larger by 57%, stored energy – by 93% and forces – by 41%.

Figure 3 shows the diagrams of magnetic field distribution in 92 mm racetrack and 110 mm shell-type quadrupole coils. The peak field point in the racetrack quadrupoles belongs to the pole turn of the second layer while in the shell-type quadrupoles it is located in the pole turn of the innermost layer. Due to that fact, the peak field in the third layer of the racetrack quadrupole is only couple percent smaller than the peak field in the second layer, which does not allow using of graded coils in racetrack quadrupoles to increase their efficiency.

The geometrical field harmonics in the racetrack and shell-type quadrupoles with different apertures are reported in Table 3. As it can be seen, the field quality is notably better in the shell-type coils than in the racetrack ones with the same number of wedges and layers.

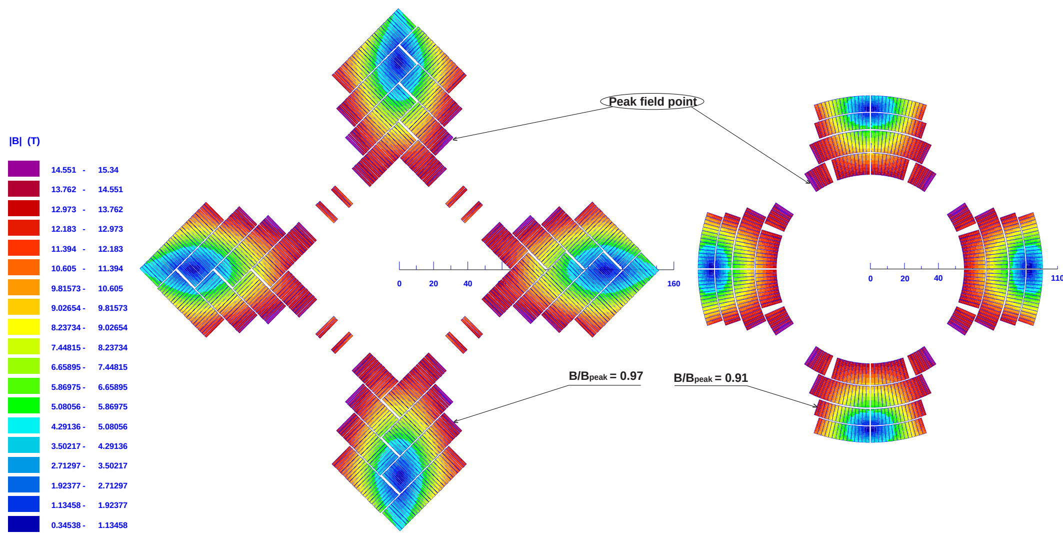

Figure 3. Diagrams of magnetic field distribution in 92 mm racetrack and 110 mm shell-type quadrupole coils.

Table 3. Systematic field harmonics at half coil aperture.

Harmonic	Racetrack			Shell		
	90 mm	**92 mm**	100 mm	90 mm	100 mm	**110 mm**
b_6	-0.0008	**0.0004**	-0.0001	0.0006	0.0005	**0.0002**
b_{10}	-0.0797	**0.1484**	0.0055	0.0045	0.0029	**0.0033**
b_{14}	-0.0529	**-0.0490**	-0.0447	0.0069	0.0046	**0.0118**
b_{18}	0.0025	**0.0016**	0.0017	-0.0047	-0.0036	**-0.0032**
a_4	0.0035	**-0.0041**	0.0039	-	-	-
a_8	0.0051	**0.0245**	0.0508	-	-	-
a_{12}	0.0040	**0.0015**	0.0027	-	-	-
a_{16}	0.0000	**0.0000**	0.0000	-	-	-

The racetrack quadrupoles have both “normal” and “skew” allowed harmonics due to the asymmetric interleaving coil design. However, the “skew” harmonics can be reduced by additional spacers and they do not limit the good field aperture in the racetrack quadrupoles. The most critical harmonic limiting the magnet good field aperture is b_{14}, which is by a factor of 5-10 larger than that in the shell-type designs.

Figure 4 shows the direct comparison of the good field regions in the racetrack quadrupole with 92 mm aperture and the shell-type quadrupole with the equivalent 110 mm aperture. The two circles represent the beam envelopes. The good field region is only 70% of the beam envelope size in the racetrack magnet, and 90% in the shell type magnet.

As it was shown in one of the previous sections, the 92 mm racetrack quadrupole in term of physical aperture is equivalent to the 110 mm racetrack quadrupole. However, to provide the same good field region the racetrack quadrupole aperture has to be increased to practically the same size as that of the shell-type quadrupole. It is clear that in this case the racetrack quadrupoles will be even less efficient then the shell-type quadrupoles.

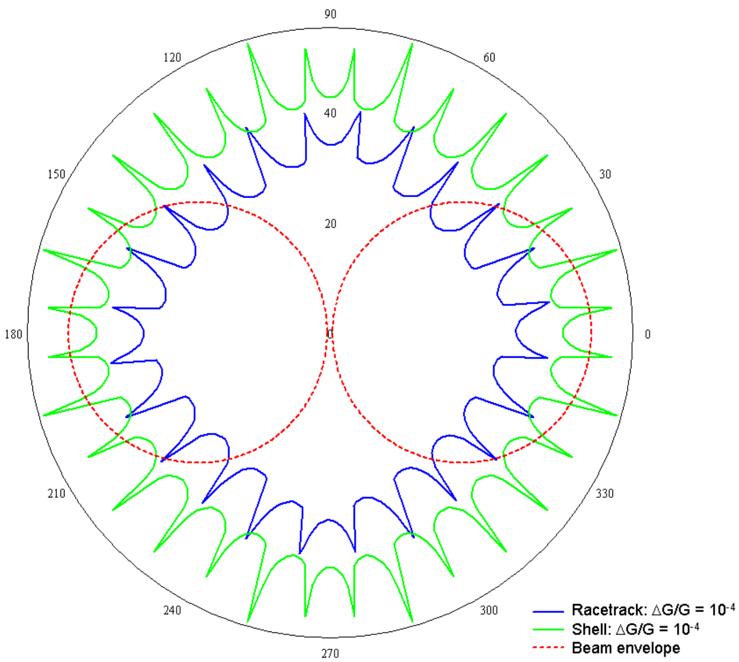

Figure 4. Contours of the 10^{-4} field deviation from the pure quadrupole field in the equivalent racetrack and shell-type quadrupoles.

Racetrack quadrupole with open midplane

The IR quadrupole magnets are exposed to high radiation loads. In order to reduce heat generation in the coil and increase the lifetime of insulation, there was made an attempt to remove a fraction of conductors from the midplane – the most irradiated region in the IR magnets. 90-mm racetrack coil presented above was appropriately modified and optimized for the best field quality. Figure 5 shows the coil cross-section with the open midplane.

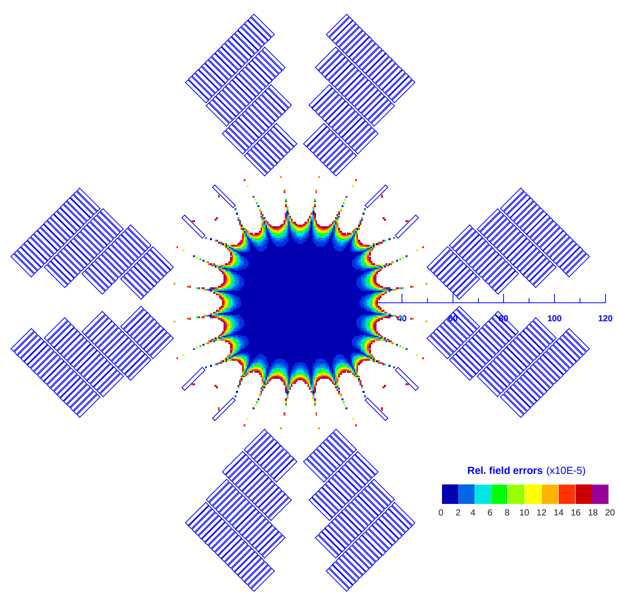

Figure 5. 90-mm racetrack quadrupole coil cross-sections with the open midplane.

In spite of the relatively large gap in the midplane, it was possible to achieve the field quality comparable to that of the original design. However, the maximum gradient in this design is only 215 T/m for the same critical current density as in all other considered coils that does not meet the requirements of LHC IR upgrade. An extra 5-7% of the gradient can be gained by a reasonable increase of the cable width that, nevertheless, is not enough for meeting the target requirements.

Conclusion

Design studies of the large-aperture Nb_3Sn quadrupoles based on the racetrack coils and their comparison with the shell-type coils have been performed and reported. In terms of the physical aperture, the 92 mm (measured in the pole plane of square aperture) racetrack quadrupole is equivalent to the 110-mm shell-type quadrupole with round aperture. To provide the same good field quality region as 110 mm shell-type quadrupole the racetrack quadrupole with the aperture of 110 mm has to be used.

The analysis and comparison of the main magnet parameters achieved in both designs with the same boundary conditions show that the racetrack quadrupole with 92-mm aperture is significantly less efficient than the shell-type quadrupole with 110-mm aperture.

The design with open midplane would be an attractive option for reduction of radiation load in the coils, however it does not provide necessary gradient even with 90-mm aperture.

References:

[1] O. Brüning, et al., LHC Luminosity and Energy Upgrade: A Feasibility Study, LHC Project Report 626, December 2002.

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[3] J.B. Strait, et al., Towards a New LHC Interaction Region Design for a Luminosity Upgrade, paper MOPA006, PAC2003, Portland (OR), 2003.

[4] A.V. Zlobin, V.V. Kashikhin and J.B. Strait, Aperture Limitations for 2nd Generation Nb3Sn LHC IR Quadrupoles, PAC2003, Portland (OR), 2003, p.1975.